Towards a Comprehensive Model for Performance Analysis of Opportunistic Routing in Wireless Mesh Networks

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Abstract—Opportunistic Routing (OR) is a promising paradigm that has been proposed for wireless mesh networks. This routing paradigm takes advantage of the broadcast nature of the wireless medium to increase the reliability of transmissions in multi-hop wireless networks. The selection of a set of candidates involves satisfying the basic requirements of the model, in which packets are forwarded toward the destination. In OR, if one of the selected candidates does not receive the packet, another candidate might be able to continue forwarding the packet. The decision of which forwarder to choose is made by coordination between candidates that have successfully received the transmitted packet. In this paper, we propose a Discrete Time Markov Chain as a general model for OR and demonstrate how it can be used to evaluate the performance of OR protocols. We also review three well-known OR protocols that we have selected as a study case. Our study demonstrates how our model facilitates better understanding of the combination of number of candidates and re-transmissions, and their significant contributions to the successful delivery of data packets. Thus, this shows that our model can help the design of future OR protocols, as well as efficient candidate selection algorithms.

Index Terms—Opportunistic routing, discrete time Markov chain model, Modeling and simulation, Performance evaluation, Wireless mesh networks.

1 Introduction

Opportunistic Routing (OR) is a paradigm used in wireless mesh networks which was proposed to cope with lossy environments; consequently, OR [1], [2] has received increasing attention from the research community in recent years. In contrast to traditional routing protocols, which use just one node as the next-hop forwarder when sending data to a given destination [3], [4], in OR the next-hop forwarder is selected from a group of candidates on-the-fly. In a traditional routing protocol, if the selected next-hop does not receive the packet, the source must retransmit the packet; in other words, all packets must traverse a pre-defined path using traditional routing methods. This link breakage on a selected path results in the need to re-construct and re-transmit the packet, thus incurring subsequent costs in terms of time and bandwidth.

The on-the-fly selection of the next-hop forwarder is the basic idea behind OR. Actually, OR takes advantage of the ability of the wireless medium to broadcast as a given packet progresses through the network. OR can benefit sparse networks or highly intense traffic networks [5] in accommodating packet flow towards a determined target. In other words, instead of establishing that a single next-hop must forward packets, OR is based on a set of nodes referred to as *Candidate Set* (CS): the potential next-hop forwarders. Note that each candidate has a priority level which determines the suitability of that candidate over others to act as the next-hop forwarder. The priority assigned to candidates is determined by certain criteria: distance to the destination, hop count, or battery constraints.

The source node includes its CS in the header of every data packet; once it has been broadcasted, each candidate that receives it can act as the next-hop forwarder. Candidates that have received the packet coordinate with each other to decide which one must forward the packet. In this way, only the most suitable candidate among all those that have received the packet will forward it, while remaining candidates will discard it. Candidate selection and coordination among candidates are the two main challenges encountered when designing OR protocols. In addition to such challenges, the main aim of an OR protocol is to reduce the *Expected Number of Transmissions* (ExNT) sent from the source to the destination, and to increase the probability of reaching the destination.

Candidate selection and coordination are the two topics most frequently investigated by the research community. In most works found in the literature, simulation performance is used as a validation tool (see references [6], [7], [8], [9], [10], [11], [12], [2]). Nevertheless, much less effort is placed on focusing on analytical models in OR, for the purpose of providing researchers with insights and information into performance that can be achieved with the use of OR. Markov processes have been used extensively to model a huge variety of stochastic processes in wireless networks. A recent study [13], [14] has shown how a Markov chain-based channel access model for a Poisson-Voronoi tessellation (PVT) can be used to evaluate the performance of a random cellular network. Using the proposed Markov model, the spatial spectrum and energy efficiencies of PVT random cellular networks has been analyzed.

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In OR, each candidate is used as the next-hop forwarder according to a given probability; therefore, several paths can be taken to arrive at the destination. These properties of an OR transmission are mapped using a Discrete Time Markov Chain (DTMC) [15]. Similar to a DTMC with the OR paradigm, the conditional probability distribution of future states of a process depends only upon the present state, and not on the sequence of events that preceded it; an OR protocol can be modeled with a DTMC.

In this paper, we present our OR based discrete time Markov chain model and show how it can be used to evaluate the performance of opportunistic routing protocols. Next, we review three well-known OR protocols that we have selected as a case to show how our model enables us to better understand how the number of candidates and the number of re-transmission parameters together contribute significantly to the successful delivery of data packets. As such, our proposed model allows us to analyze the performance of any OR algorithm in terms of the probability of reaching the destination from the source node; the *Expected Number of Transmissions from the source to the destination (ExNT); the probability distribution* of the number of transmissions; and the expected hop-count of packets delivered to the destination. The only inputs in our Markov model are the Candidate Set (CS) and the link probability to each of them, in addition to the maximum number of re-transmissions of a packet in the event that it is not delivered to any candidates. Therefore, the proposed model does not rely on any specific assumptions about the network topology, nor the mechanism for candidate selection and prioritization of candidates. To the best of our knowledge, this work is among the first studies investigating the effect of the number of re-transmissions of each node, in the event that a packet does not reach any of the candidates. Our model enables the evaluation of the impact of a limited number of re-transmissions on the performance of OR; it also assesses whether or not the use of OR and several candidates can compensate for the need to re-transmit. The proposed model is shown to be flexible enough to work as an analysis tool for studying the behavior of new candidate selection solutions, and for evaluating their benefits compared to previous methods.

The remainder of this paper is organized as described in the following text. Section 2 presents related work. Section 3 introduces the proposed Markov model. Section 4 provides an overview of the three OR protocols under study. Section 5 describes the methodology used to evaluate the proposed model, including network scenario, propagation model, and metrics under study. Section 6 discusses the observed analytical model and the experimental results. Finally, Section 7 concludes the paper and provides directions for future work.

2 Related work

Several analytical approaches address different aspects of OR in the literature. An analytical study of OR for finding the maximum progress distance was proposed in [16]. The model does not rely on a specified candidate selection algorithm, and estimates only the expected progress distance of the transmitted packets. However, the other models do not consider re-transmission mechanisms when none of the candidates receives the packet.

Another approach [17] is based on the claim that transmitting packets at different rates may increase the throughput of OR; however, the communication range associated with different rates must also be taken into account. In addition, a lower transmission rate can achieve better throughput than a higher one in some conditions, due to the longer transmission range.

Two algorithms have been proposed in [18] to find the optimal candidate set in the case of the constrained and the unconstrained number of candidates. The algorithms present constrained and unconstrained versions for finding the optimum candidate list, considering the trade-off between the probability of reaching the destination and the number of transmissions.

A Markov model to evaluate the performance of OR was proposed in [19]. In this model, an infinite number of re-transmissions was considered for the failure of transmission. On the contrary, we limit the number of times that a node can re-transmit a packet; a low number of re-transmissions can considerably improve network performance, so it is unnecessary to allow an infinite number of retries. In [20], a *random walk* model, Markov model, is used to analyze the end-to-end transmission cost of different routing mechanisms. However, their model assumes that a packet can be re-transmitted indefinitely until it finally reaches the destination.

There have also been efforts to find an optimal candidate set. Authors in [21] proposed an analytical model to describe the procedures that occur according to OR. The model is used to derive a closed-form formula of the average number of transmissions needed to deliver a packet from source to destination using OR. Mingming Wu et al. [22] proposed a utility-based OR to balance the trade-off between the cost of transmitting a packet and transmission reliability. They proposed an optimum candidate selection algorithm that maximizes the OR utility function. The work described in [23] computes the best position of nodes to act as candidates. This positioning aspect is important in the sense that locating the candidates near the optimal places in a static network enables the network to benefit the most from OR.

In addition to the analytical studies in OR, the idea of Network Coding (NC) is used in OR to improve the network performance and reduce the cost of candidate coordination [24], [25], [26], [27], [28], [29]. The general idea of NC is to combine multiple packets into one packet, transmit it, and retrieve the original packets in the destination. In other words, the flow in NC technique is divided into batches. The source node creates a linear combination of the original packets and broadcasts the packet. Each candidate which receives the packets forward them if they are linearly independent. When the destination receives enough packets to decode, it retrieves the original packets from the decoded ones.

As an example of OR protocols that uses the idea of network coding, we can mention one of the most referenced protocols called MAC-independent Opportunistic Routing & Encoding (MORE) [27]. MORE divides the flow to some batches and selects candidates based on the Expected Transmission Count (ETX). A linear combination of packets in a batch is created, and the list of candidates is added to the data header. After broadcasting the packet, each receiving node must check the independence of the packets from those it has previously received. If the recently received packet is linearly independent from earlier packets, the node then creates a new linear combination of packets before forwarding. Authors in [24] proposed COPE, in which nodes perform XOR over packets it has intended to send. The nodes perform XOR over the overheard packets if they ensure that their neighbors can decode the packet.

Using the idea of NC with OR may cause a steep increase in packet transmissions in the network, since each candidate which receives the packet can forward it. Therefore, to ensure that the destination is able to decode and retrieve the original packets and reduce the number of packet transmissions along the network, there must be a compromise when forwarding sufficient numbers of coded packets [2].

3 Analytical Model

There are close similarities between a Discrete Time Markov Chain (DTMC) [15] and OR if there is a perfect coordination between OR candidates, and the set of candidates chosen for the transmission is independent of the ones used in previous transmissions. Note that when we refer to perfect coordination in OR terminology, we mean that more than one candidate receives a packet, and only the one with highest priority continues to forward the packet while the others discard it. Furthermore, each candidate is used as the next-hop forwarder according to a given probability, so there can be several paths used to arrive at the destination. As we can see, the properties of an OR transmission are very similar to those of a DTMC. Therefore, due to the lack of analytical models that support the evaluation of OR solutions, we have developed a model that aims to present an approach that is as inclusive as possible. The solution covers any network topology and candidate selection algorithm. In such scenarios, failures to transmit packets are contemplated by introducing a number of re-transmissions as a major parameter in defining the model. The mapping of such cases is performed through the modeling of OR by employing a Discrete Time Markov Chain (DTMC) technique.

3.1 Markov Modeling

The DTMC technique is used to model OR on the grounds that each state in the defined OR model is mapped as a stochastic process. For this mapping, the Markov properties hold up under any situation encountered by the model; these situations involve transition rules depending only on the present state. This memoriless characteristic constitutes the Markov process and guides the definition of the states of our proposed model. Thus, the states of our model have been identified as a tuple composed of the current network node ID and the number of transmission attempts made by the same node.

3.2 Markov Model and Opportunistic Routing

At this stage of the modeling process, an assumption regarding the OR candidate coordination is required to enable simplicity in the model; it is assumed that there is perfect

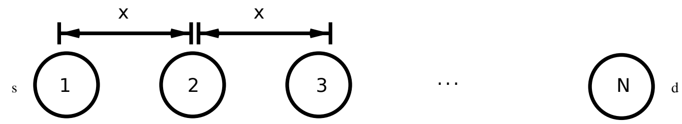

Fig. 1. Linear topology

coordination among selected candidates for each transmission. There are some proposed methods in the literature, such as a three-way handshake or RTS-CTS coordination, which can provide perfect coordination in OR. However, the focus of this work is on the application of the DTMC modeling on OR, and to see the difference between the analytical results obtained using the proposed DTMC and the results produced through simulation; so, to simplify the initial assessment, the coordination between candidates is left outside the scope of our work. As a result of this supposition, the decision regarding which candidate should forward the packet is always settled, and only one candidate forwards the received packet to the next CS in the network; this transmitted packet will reach the next-hop according to a determined probability.

The transmission of packets in the OR model occurs independently of the operation of the previous visited states; it only considers the probability of success when transmitting a packet between two particular nodes. Consequently, each candidate might receive a packet from the respective previously transmitting node under a given probability, and the candidate will transmit this packet to its next-hop candidates; this routing process occurs until the packet finally reaches the destination or is dropped by any node in the path between the source and the destination.

Following this characteristic transition, we can identify a close resemblance between the properties of OR and the Markov process. In a Markov chain, every state of the model is strictly defined by the Markov property; this regards only the current step and ignores any previous states when performing the current decision on a state transition. Furthermore, the peculiarity of the routing that defines when a packet has reached the destination or failed to be delivered results in absorbing states in a Markov process. Due to this closeness, packet transmissions are directly converted into state transitions in the OR Markov model.

3.2.1 *Modeling of a Linear Topology*

Consider the linear network topology shown in Figure 1; it contains N nodes numbered from 1 to N and equally spaced x meters, with s and d as the source and the destination, respectively. In this topology, there is an ordered CS used to reach destination d from s; this set is defined as $C_d^s = \{c_1, c_2, ..., c_{ncand}\}$, where $ncand$ is the number of candidates. The set contains a list of candidates ordered according to their priority. This priority is defined by a policy and determines the use of a node as a next-hop forwarder for a given source; thus, the nodes in the list present priorities as $c_1 > c_2 > \cdots > c_{ncand}$. This means that candidate c_j forwards a packet only if none of its respective higher-priority candidates ($c_i, i < j$) receive the packet.

Following this transmission strategy, a packet is always forwarded by the candidate with the highest priority that has received the packet. Upon the broadcasting of the packet, the lower-priority candidates discard the same packet received. This situation is assured to happen with the assumption that a perfect coordination between candidates exists, which prevents collisions and duplicate transmissions. Also, a node can re-transmit a packet at most K times in order to increase the chance of having it delivered to any of its candidates. Note that K is the maximum number of re-transmissions of a packet in each node. This process repeats for every hop in between the source and the destination the packet advances in the path until it either reaches the destination or is discarded by any of the intermediate nodes, after K failed re-transmissions.

According to the linear network depicted in Figure 1 and the assumed OR protocol, we can model this simple topology using a Discrete Time Markov Chain (DTMC), as described in Figure 2. In this model, we have also assumed that the number of candidates for each node is 2 ($ncand = 2$) for the sake of clarity. Every Markov chain model is composed of two basic parts, states and transitions. We have therefore modeled this topology by mapping each transmission attempt of every node as a state in the Markov chain. In this case, the state in the model is composed by a tuple, which identifies the node and the respective number of transmissions that it has attempted for the same packet to reach the destination. The transitions in the model are consequently representations of each attempt to send a packet towards the destination; every attempt leads the model to a different state. In line with the model displayed in Figure 2, the success of transmitting a packet towards the destination is represented in the model by its movement to a state at the right; on the other hand, the failure to transmit a packet is illustrated in the model by its movement to a state downwards. As we mentioned above, in the proposed model, each state is defined as a tuple. The tuple, <ID, re-tx>, consists of an *ID* and a *re-tx*. The *ID* represents the identification of a node and the *re-tx* shows the number of times a packet has been re-transmitted by the respective node. Thus, the number of nodes and the maximum number of re-transmissions, K, are the parameters delimiting the number of possible states in the model.

It is worth noting in Figure 2 that the rectangles delimited by the dashed lines group the states that indicate the re-transmission of nodes. These re-transmissions are triggered only if none of the respective candidates of a node receive the packet during the previous transmission attempt. Finally, the Markov model presents two absorbing states: *Dest* and *Fail*. The *Dest* state represents the successful delivery of a packet to its final destination. The *Fail* state relates to a number of re-transmissions in each node exceeding the limit K; therefore, in this case the packet does not reach the final destination, generating a packet drop.

An observation of Figure 2 shows that all states depicted in the first row of the model diagram, $< i, 0 >$ ($i \in 1, 2, \ldots, N-1$), represent the nodes that have successfully transmitted a packet to their candidates in the first transmission attempt (re-tx=0). In the case event that a packet cannot be delivered to any of the candidates during the first attempted transmission, a re-transmission depending on the value of K is needed. In this case, the states indicated on the second row in the model diagram represent this situation; this situation is delimited by $< i, 1 >$, $i \in \{1, 2, \ldots, N-1\}$ and means that one re-transmission was needed to complete the delivery of a packet at a given moment. Extending this trend of thought further, the other following rows in the below diagram represent the other re-transmission attempts; these are limited by re-tx=K times. In the event that a node cannot deliver a packet to its respective candidates in K re-transmission attempts, the node is not allowed to re-transmit the packet. This causes a failure to transmit the packet to the destination and results in a packet drop; this situation is modeled by the scenario in which the *Fail* absorption state is reached. On the other hand, if no node drops the packet, the packet ultimately reaches the destination node. This successful delivery of the packet to its final destination is represented by the transition in the model that leads to the *Dest* absorption state. Moreover, whenever a node successfully delivers a packet within the K allowed number of re-transmissions, the packet transmission passes through the same process again. This means that the new node, the candidate that has just received the packet, needs to transmit it within K number of re-transmissions. In order to represent this behavior through the model, there exists only transitions from the re-transmission states to the states in the first row of the model.

$$\begin{aligned} p_1 &= p(2x), \\ p_2 &= p(x) \times (1 - p_1), \\ p_3 &= 1 - (p_1 + p_2), \\ p_1' &= p(x), \\ p_3' &= 1 - p_1'. \end{aligned} \tag{1}$$

A transition matrix is then designed according to the state and transition definitions in the Markov model. In this matrix, each transition is represented by its respective probability. This probability is obtained from the success ratio for transmitting a packet between two nodes. Consequently, some assumptions are defined in order to obtain such probabilities and to assemble the transition matrix. The first assumption defines a function that returns the probability of reaching a node $p(x)$, within a given distance x. The second assumption is related to the priority of each candidate. As mentioned in the beginning of this section, each candidate has a priority that corresponds to the candidate's distance to the destination in the case of a linear topology. This means that candidates will have higher priority when in close proximity to the destination. The third assumption considers the existence of the perfect coordination within a set of candidates, so no conflicts arise when defining the candidate for packet transmission. For example, following this last assumption, in a set of two candidates, the candidate with the lowest priority (c_2) forwards a received packet only if the other candidate (c_1), presenting the higher priority, does not receive the packet. Thus, according to the assumed function, the probability (p_1) of the candidate c_1 in Figure 2 is $p(2x)$, because the candidate is at a distance of $2x$ from the sender node. Moreover, the candidate c_2 forwards the packet with probability p_2, which represents the chances of c_1 not receiving the packet and c_2 receiving the packet. In the event that neither candidates c_1 nor c_2 receive the transmitted packet, the source node re-transmits the packet with probability p_3; this is depicted in Figure 2. In the last hop of the linear topology, the model represents

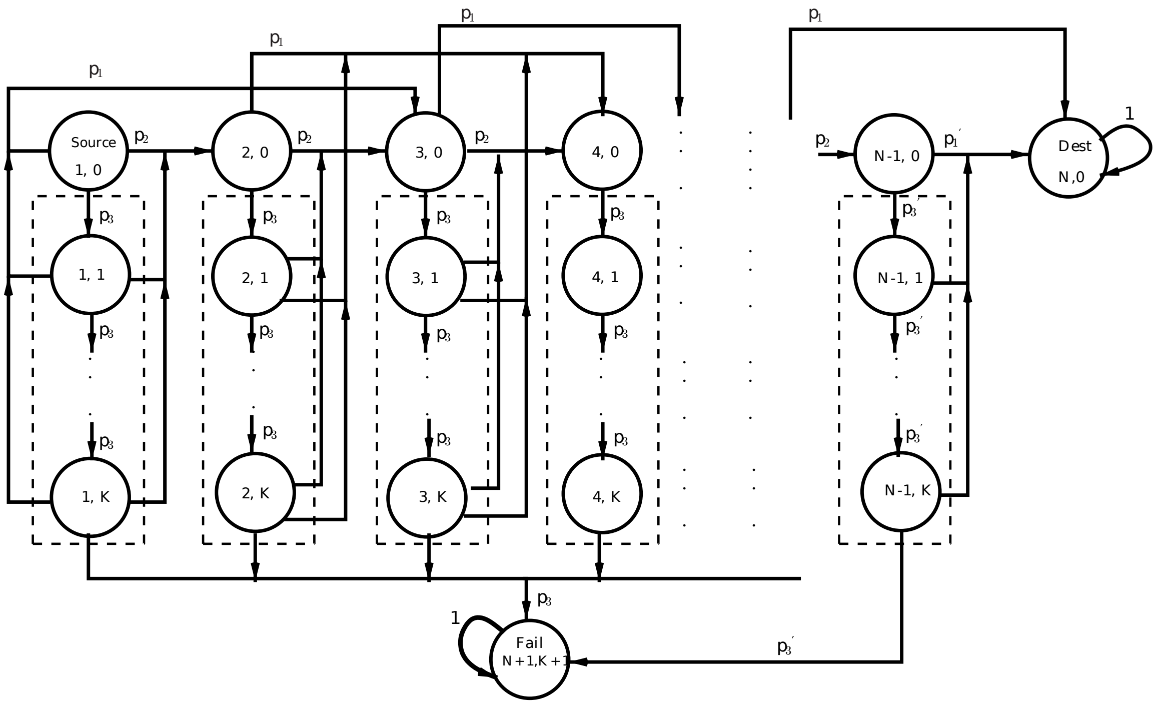

Fig. 2. Markov Model for 2 candidates

the successful transmission to the final destination as p'_1 and the failure to perform the transmission as p'_3, leading to a re-transmission or to the *Fail* state. The probability that each transition may occur between a pair of states is defined according to Equation 1.

It is worth noting that the Markov model presented in Figure 2 and the transition matrix described in the previous paragraphs are constructed based on the simple linear topology depicted in Figure 1; they are limited to 2 candidates and K re-transmissions. A general mapping of the proposed model is presented in Section 3.2.2; this generic OR model is needed in order to usefully apply the model to more complex network topologies. This is fitting for a flexible number of candidates and a variety of selection algorithms.

3.2.2 General-Purpose OR Model

As described in the previous section, the OR model obtained from a linear topology is independent of the network topology, the number of candidates, and the candidate selection algorithm; we have used $ncand = 2$ as the maximum number of candidates per node. However, a Markov chain model can be obtained similarly but with any other number of candidates ($ncand$). The only restriction for generating a transition matrix in any case is providing the data for the defining parameters. These correspond to the following characteristics for each node: the number of candidates ($ncand$), the maximum number of allowed re-transmissions (K), and the link probability with other nodes.

The transition matrix is built up with the transition probabilities between the defined states. The states are defined using the same rule as described in Section 3.2.1. Thus, for a network containing N nodes that are allowed to re-transmit K times, the number of transient states in the model is $(N-1)\times(K+1)$. In addition to the transient states there are two absorbing states that result in success or failure in reaching the destination node. As a result, the transition probability matrix presents a dimension equal to $[(N-1)\times(K+1)+2]\times[(N-1)\times(K+1)+2]$.

In the transition matrix, each state is identified as a tuple: <ID, re-tx>. This index in the transition probability matrix delimits each transient state, except for the Destination state *Dest* and the failure state *Fail*. The index for each state in the matrix is defined by the ID of a node and by the number of re-transmissions: *index*=ID+(re-tx)$\times(N-1)$. The absorption states are identified according to $index = (N-1)\times(K+1)+1$, for the state that represents the occurrence of a packet drop (*Fail*), and according to $index = (N-1)\times(K+1)+2$; the latter is the case for the state that corresponds to reaching the destination node (*Dest*). With these parameters taken into consideration, a general-purpose transition matrix is provided in Equation 2. In this equation, the two right-hand columns of the transition matrix represent the probability transitions from other states to the absorbing states. The transitions among the transient states in the matrix are represented by $p^{(i,j)}_{(i',j')}$; this represents the transition from state (i,j) to (i$'$,j$'$).

The transition probabilities in the devised model derive from packet transmission conditions between network nodes. Observing this fact, the probabilities are defined according to the terms in Equation 3. For this equation, the set of candidates is defined by $c_i(l) \mid l \in \{1,2,\ldots,ncand\}$, which delimits the candidate of node i with priority l. The first term in the equation concerns the probabilities for the transitions reaching the state $< c_i(1), 0 >$ from any state $< i, j >$, where i $\in \{1,2,\ldots,N-1\}$ and j $\in \{0,1,\ldots,K\}$. This represents the probability of reaching the candidate $c_i(1)$ from node i. The second term in Equation 3 refers to the transition probability of reaching states that represent candidates with lower priorities, such as $c_i(j) \mid j = \{2,\ldots,ncand\}$. The third term in this equation delimits the probabilities for transitioning into states where packet

$$P = \begin{array}{cc} & \begin{array}{cccc|cc} (1,0) & (2,0) & \dots & (N-1,K) & Fail & Dest \end{array} \\ \begin{array}{c} (1,0) \\ (2,0) \\ \vdots \\ (N-1,K) \\ Fail \\ Dest \end{array} & \left(\begin{array}{cccc|cc} p^{(1,0)}_{(1,0)} & p^{(1,0)}_{(2,0)} & \dots & p^{(1,0)}_{(N-1,K)} & p^{(1,0)}_{Fail} & p^{(1,0)}_{Dest} \\ p^{(2,0)}_{(1,0)} & p^{(2,0)}_{(2,0)} & \dots & p^{(2,0)}_{(N-1,K)} & p^{(2,0)}_{Fail} & p^{(2,0)}_{Dest} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ p^{(N-1,K)}_{(1,0)} & p^{(N-1,K)}_{(2,0)} & \dots & p^{(N-1,K)}_{(N-1,K)} & p^{(N-1,K)}_{Fail} & p^{(N-1,K)}_{Dest} \\ \hline 0 & 0 & \dots & 0 & 1 & 0 \\ 0 & 0 & \dots & 0 & 0 & 1 \end{array}\right) \end{array} .(2)$$

$$p^{i,j}_{i',j'} = \begin{cases} p(i, c_i(1)), & \text{if } 1 \leq i \leq N-1, i' = c_i(1), 0 \leq j \leq K, j' = 0. \\ p(i, c_i(m)) \prod_{l=1}^{m-1} (1 - p(i, c_i(l))), & \text{if } 1 \leq i \leq N-1, i' = c_i(m), 0 \leq j \leq K, j' = 0, \\ & \quad m = 2, \dots, ncand. \\ 1 - \sum_{l=1}^{ncand} p^{i,j}_{c_i(l),0}, & \text{if } (1 \leq i \leq N-1, i' = i, 0 \leq j < K, j' = j+1) \quad \textit{or} \\ & \quad (1 \leq i \leq N-1, i' = (N+1), j = K, j' = j+1). \\ 1, & \text{if } (i = i' = N \text{ and } j = j' = 0) \quad \textit{or} \\ & \quad (i = i' = (N+1) \text{ and } j = j' = (K+1)). \end{cases} \tag{3}$$

re-transmissions occur. The fourth term in Equation 3 relates to the probability of remaining in the same state during each transient state; it is worth noting that the probability of remaining in the same state in the context of states *Dest* and *Fail* is equal to 1.

The transition matrix, called P, is expressed in the canonical form for the sake of simplicity, as shown in Equation 4. In this form $\mathcal{Q}$, which represents the dimensions $(N-1)(K+1) \times (N-1)(K+1)$, is related to the transient states; it involves the transition probabilities between these states. $\mathcal{R}$ on the other hand represents the dimensions $(N-1)(K+1) \times 2$, and groups all transition probabilities from the transient states to the absorbing states. Finally, I is an identity matrix of dimension 2×2 and represents the transitions within the absorbing states.

Therefore, after defining the Candidate Set (CS) for each node and delimiting the maximum number of re-transmissions, the transition probability matrix can be generated. From this matrix, an analysis can be performed, and values may be obtained for different metrics.

$$\mathcal{P} = \begin{bmatrix} \mathcal{Q} & \mathcal{R} \\ 0 & \mathcal{I} \end{bmatrix} \tag{4}$$

3.3 OR Analysis Metrics

The obtained matrix P of a given model enables a thorough analysis of performance, effectiveness, and efficiency on the observed OR solution incorporated in the proposed model. In terms of metrics for evaluating such aspects, some of them have shown to be essential for providing insights into verifying the feasibility of a given OR solution. These metrics are the probability of a successful packet delivery from source to destination using OR, the probability of a failed transmission, the *Expected number of transmissions* (ExNT) required to deliver a packet to the destination, the percentage of delivered packet to the destination for a given number of transmissions, and the expected hop-count from source to the destination. All these metrics have been derived from matrix $\mathcal{P}$.

3.3.1 Probability of packet delivery

The probability of delivering a packet to the destination node is obtained by calculating the probability of reaching the destination state (*Dest*) from the initial state (*Source*); this represents a given source node, which is the originator of the transmission. Since a packet might need to be transmitted several times along the path between the source and the destination, the final probability of reaching the destination takes into account a set of one or more interdependent transmissions and re-transmission transitions. The transition matrix $\mathcal{P}$, which contains the probability for each transition between a pair of states, is used to obtain the probability of reaching *Dest* in h steps, or transitions. The probability of reaching the destination in h steps is obtained by calculating $\mathcal{P}$ to the power of h. $\mathcal{P}$ power h described in the nominal form of the transition matrix is provided by Equation 5.

$$\mathcal{P}^h = \begin{bmatrix} \mathcal{Q}^h & (\mathcal{I} + \mathcal{Q} + ... + \mathcal{Q}^{h-1}) \times \mathcal{R} \\ 0 & \mathcal{I} \end{bmatrix} \tag{5}$$

By obtaining the stationary state $h \to \infty$ of a given $\mathcal{P}$, the *fundamental matrix* of the Markov process $\mathcal{N} = (\mathcal{I} + \mathcal{Q} + \mathcal{Q}^2 ... + \mathcal{Q}^{h-1}) = (\mathcal{I} - \mathcal{Q})^{-1}$ may be retrieved. Through $\mathcal{N}$, the probability of reaching the absorbing state from any other transient state is calculated by $\mathcal{N} \times \mathcal{R}$. Moreover, only the path from the source to the destination is considered when retrieving the probability of delivering a packet; thus, an initial distribution of states is defined according to Equation 6. Consequently, the probability of reaching any other transient state from the source after h steps is delimited by $v \times \mathcal{P}^h$, which relates to the first row of $\mathcal{P}^h$. On the obtained matrix $\mathcal{N} \times \mathcal{R}$, the element p_{11} refers to the probability of dropping a packet (p_{Drop}), which was initially transmitted by the source (see Equation 7). In the same matrix, the element p_{12} shown in Equation 7 represents the probability of transmitting a packet from the source and successfully reaching the destination, $p_{Success}$.

$$v = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix} \tag{6}$$

$$\begin{aligned} p_{Drop} &= (\mathcal{N} \times \mathcal{R})_{11} \\ p_{Success} &= (\mathcal{N} \times \mathcal{R})_{12} \end{aligned} \tag{7}$$

3.3.2 Expected number of transmissions

The Expected Number of Transmissions (ExNT) is a metric that provides an understanding of the effort required for the successful delivery of a packet from a given source to a destination. The effort corresponds to the amount of consumed resources and time represented in accordance with each transmission attempt. This metric also fits the main objective of OR, which consists of decreasing the number of expected transmissions, enabling a more efficient routing.

This metric is retrieved from the Markov model based on the transition probabilities. First, consider X as a random variable that contains the number of transitions from state i to the destination absorbing state *Dest*. For a given transient state i, the entry $q_{i,j}$ of $\mathcal{Q}^{h-1}$ in matrix $\mathcal{P}^{h-1}$ provides the probability of transitioning to the transient state j in exactly $h-1$ steps. Evolving from this concept, Equation 8 defines the probability of transitioning from a non-absorbing state i to an absorbing state j in precisely h steps.

$$p[X = h] = \mathcal{Q}^{h-1} \times \mathcal{R} \tag{8}$$

The matrix resulting from $\mathcal{Q}^{h-1} \times \mathcal{R}$ has dimensions $(N-1)(k+1) \times 2$; the ExNT is obtained from the expected value of X. The expected value of X is derived from Equation 9, which shows matrices divided element by element.

$$\begin{aligned} E[X] = \; & \frac{\sum_{h=1}^{\infty}(h \times p[X = h])}{p[X = 1] + p[X = 2] + \ldots} = \\ & \frac{1 \times \mathcal{R} + 2\mathcal{Q} \times \mathcal{R} + 3\mathcal{Q}^2 \times \mathcal{R} + 4\mathcal{Q}^3 \times \mathcal{R} + \ldots}{\mathcal{R} + \mathcal{Q} \times \mathcal{R} + \mathcal{Q}^2 \times \mathcal{R} + \mathcal{Q}^3 \times \mathcal{R} + \ldots} = \\ & \frac{(\mathcal{I} - \mathcal{Q})^{-2} \times \mathcal{R}}{(\mathcal{I} - \mathcal{Q})^{-1} \times \mathcal{R}} = \frac{\mathcal{N}^2 \times \mathcal{R}}{\mathcal{N} \times \mathcal{R}} \end{aligned} \tag{9}$$

As we can see in Equation 9, the expected number of transmissions of a packet is conditioned to the case that the packet is delivered to the destination. Therefore, the denominator of Equation 9 shows the probability of delivering the packet to the destination ($\mathcal{N} \times \mathcal{R}$).

3.3.3 Probability of number of transmissions

In Section 3.3.1, we showed how to obtain the delivery probability for arriving at the destination state. In this section, we explain how to obtain the probability distribution of the number of transmissions by using the proposed model.

If we assume that the source ID is equal to 1, the element $p_{1,((N-1)\times(K+1)+2)}$ in Equation 5 is the probability that with one transmission the packet will be delivered to the destination from the source node. The probability that the packet reaches the destination (*Dest* state) from the source node with h transmissions is the element $p_{1,((N-1)\times(K+1)+2)}$ in the matrix $\mathcal{P}^h$. Since we are interested in the *probability distribution function* (PDF) of packets delivered to the destination, we also need to consider the probability of arriving at the destination. Therefore, the probability for the number of transmissions required to deliver packets to the destination can be obtained by using Equation 10.

$$Probability\_Distribution = \frac{p^h_{1,((N-1)\times(K+1)+2)}}{(\mathcal{N} \times \mathcal{R})_{1,2}}, \quad h \in \{1, 2, \ldots, \infty\}. \tag{10}$$

Recall that $\mathcal{N}$ in Equation 10 is the fundamental matrix of the Markov process, which is equal to $(\mathcal{I} - \mathcal{Q})^{-1}$, as explained in Section 3.3.1.

3.3.4 Hop-count

The hop-count represents the length of a path: the expected number of hops traversed to reach a destination from a given source. In order to obtain the number of hops traversed before a packet is dropped or delivered to the destination, only the visited states where re-transmission does not occur ($< i, 0 >, i \in \{1, 2, \ldots, N-1\}$) are considered; this line of thinking discards the absorbing states. This means that the hop-count before delivering a packet to the destination can be retrieved by only considering the visited states that are in the first row of the model seen in Figure 2. Consequently, in order to impose this restriction on the model, the transmission states for the same node are merged together into one new state; this takes into consideration all the successful transmissions and the re-transmissions of the node. Figure 2 shows the states of re-transmission for respective nodes inside dashed rectangles; all the states of re-transmission are removed in the new modeling.

In the new Markov model, each state denotes the node that transmits a packet. As a result, the transition probabilities between states now express the probability of processing a packet, accumulating the previous probabilities for transmissions and for the re-transmissions allowed for each node. Since it is a matter that involves the increasing abstraction of the model, the new model depicted in Figure 3, can be easily generated from the initial model, presented in Figure 2. The new transition probabilities between states are calculated according to Equation 11 and from the probabilities shown in Equation 3. In Equation 11, the probability of a node delivering a packet to its first candidate with the first transmission or by any other re-transmission is denoted by p_1^{hc}; similarly, p_2^{hc} represents the probability that the packet will be transmitted by the second candidate. Most notably, in the case where there are only two candidates, the probability of dropping a packet after $K+1$ transmission attempts, or of reaching the *Fail* absorption state, is represented by p_3^{hc}. Another transition

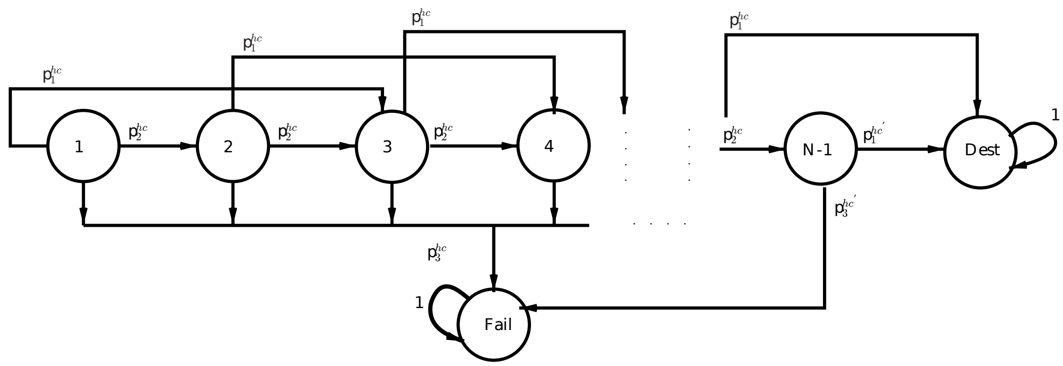

Fig. 3. Re-configured Markov Model used to calculate hop-count

probability matrix is generated from these probabilities; the expected hop-count required to deliver a packet to the destination is then obtained through the same equation as ExNT (see Equation 9).

$$\begin{aligned}
p_1^{hc} &= p_1 + p_3 \times p_1 + (p_3)^2 \times p_1 + \cdots + (p_3)^K \times p_1 = \sum_{i=0}^{K} (p_3)^i \times p_1, \\
p_2^{hc} &= p_2 + p_3 \times p_2 + (p_3)^2 \times p_2 + \cdots + (p_3)^K \times p_2 = \sum_{i=0}^{K} (p_3)^i \times p_2, \\
(p_1^{hc})' &= p_1' + p_3' \times p_1' + (p_3')^2 \times p_1' + \cdots + (p_3')^K \times p_1' = \sum_{i=0}^{K} (p_3')^i \times p_1', \\
p_3^{hc} &= (p_3)^{K+1}, (p_3^{hc})' = (p_3')^{K+1}.
\end{aligned} \tag{11}$$

4 Opportunistic routing protocols under study

The main objective of this paper is to use the proposed Markov model to evaluate the performance of different OR protocols. Therefore, before using the Markov model to evaluate the performance of OR protocols, in this section we introduce three well-known OR protocols that have been proposed in the research of this field of study. We have selected three different OR protocols with different features and metrics for the purpose of selecting candidates. As a simple and, in turn, the most well-known OR protocol, we have selected Extremely Opportunistic Routing (ExOR) [1], [30]. The Shortest Path First (SPF) algorithm with Expected Transmission count (ETX) as the weight of links is used to find the candidate set. In order to assign a priority to each of the selected candidates, the ETX of each candidate to the destination is used; the candidate with the least ETX to the destination receives the highest priority. Distance Progress Based Opportunistic Routing (DPOR) [31] was chosen to evaluate the performance of an OR protocol which selects candidates based on local information. DPOR uses a new metric called *Expected Distance Progress* (EDP) which considers the closeness of neighboring nodes and the link delivery probability between a node and its neighbors to select candidates. Finally, Minimum Transmission Selection (MTS) [32] was chosen as an optimum protocol which selects the optimum set of candidates. MTS uses *Expected Anypath Transmissions* (EAX) [32], which captures the expected number of transmissions from source to the destination using OR.

5 Analysis Methodology

In this section, we describe the methodology employed to evaluate the performance of the OR protocols using the proposed Markov model. In Section 6, we will provide both analytical results, obtained with R [33], and simulation results, obtained with NS2.35 [34]. Our main objective is to compare the analytical results obtained using our Markov model with the simulation results for different scenarios and OR protocols.

Each OR protocol consists of two main parts: candidate selection and candidate coordination. As we mentioned in Section 3, in our proposed model, we have assumed that there exists a perfect coordination between candidates. This means that the highest priority candidate, which has successfully received the packet, will forward the packet while the others will simply discard it. In order to be more precise and to compare the analytical results with the simulation results, we implemented the candidate coordination phase of the OR protocols under study in two different conditions. In the first implementation of candidate coordination, we considered the perfect coordination between the candidates which had received the packet. Therefore, the behavior of candidate coordination in each OR protocol in the simulation environment is the same as for the Markov model. In the second approach of our candidate coordination implementation, we implemented the well-known *Timer-based* coordination [30], [2] for all of the OR protocols under study; this is because our main target in this paper is to evaluate the proposed Markov model and to compare the analytical results with the simulation experiments. The investigation of different methods of candidate coordination is outside the scope of this paper. Note that DPOR and MTS already use the Timer-based approach for candidate coordination. We have changed the method that ExOR employs to coordinate the candidates from the ACK-based [1] to the Timer-based approach to produce the same condition for all protocols under study.

In the Timer-based coordination approach, each candidate $c_i(l)$ waits for a period of time T_l before forwarding the packet. The higher the priority of the candidate is, the less the waiting time becomes. We have used $T_l = (l-1) \times T_{Default}$ for the waiting period of candidate $c_i(l)$ before its transmission may occur; here, l is the priority order of that candidate and $T_{Default}$ is a pre-defined time. By using T_l, the highest priority candidate ($c_i(1)$) will not wait and the second candidate ($c_i(2)$) will wait for $1 \times T_{Default}$ and etc.

In Section 6, we will compare the analytical results obtained from the Markov model with the experimental ones obtained through the simulation. Therefore, in Section 6 we will show the analytical results obtained from the Markov model for different protocols under study; and, in a separate graph, we will show the differences between the simulation and the analytical results.

5.1 Scenario

In order to compare the analytical and simulation results, we have created the same network topology in both environments (R and NS-2); thus, the position of nodes and the selected CS in NS-2 are the same as those defined in R. To do this, we have created the scenarios and the CS using R and we have exported them to NS-2. Recall that, our Markov model is independent of the network topology and the candidate selection algorithm. The only inputs needed in our model are the following: the candidate set, $C_i^D = \{c_i(1), c_i(2), \ldots, c_i(ncand)\}$; the delivery probability of reaching the candidates; and the maximum number of re-transmissions, K, allowed in each node. For the topology scenario, we considered a square with sides equal to 400 m. We placed the source and destination at the end points of the diagonal of the square. The number of nodes in our wireless mesh scenario varied from $N = 45$ to 100 nodes; these nodes were randomly placed in a square-shaped 2D environment. For each number of nodes we generated 100 different positions, each point of the obtained results is the average of 100 runs. In the simulation results, we have used IEEE 802.11 as the Medium Access Control (MAC) protocol.

The source node generates Constant Bit Rate (CBR) traffic with 1 packet per second, which has 512 bytes of payload. Note that this sending rate was selected to challenge the abilities of the routing protocol to successfully deliver data packets in a wireless network, and does not represent any particular class of applications. However, it can be considered a simple broadcasting application. The source sends packets for the duration of the simulation, which lasts for 5000 seconds. Through extensive experimental analysis on this scenario, the results showed that above 5000 packets (5000 seconds simulation time), the variations on the results are negligible.

The number of candidates affects the performance of the OR protocol. To evaluate the effects of the number of candidates on the OR protocols under study, we have used different maximum numbers of candidates in each node; thus $ncand = 2, 3, 4, 5$. Another parameter that results in a high impact on the performance of OR protocols is the maximum number of re-transmissions when none of the candidates of a respective node receive the packet. As we have mentioned in Section 3.1, we have considered the maximum number of re-transmissions in the proposed Markov model as a parameter by which to evaluate the performance of OR protocols. The maximum number of re-transmissions in our analytical and simulation results varies as re-tx$= 0, 1, \ldots, 5$ and 10.

5.2 Propagation model

Two well-known models, free space and two-ray ground propagation, consider the received power of the sender as a deterministic function of distance. In other words, these two models consider the communication range as a perfect disk. If a node is located within this disk, it will receive the transmitted packet, while the nodes outside of this range will not receive the packet. In reality, due to multi-path propagation effects, the received power at a certain distance is a random variable. Therefore, we have used the shadowing propagation model, which considers the received power as a random variable due to fading effects. Two important parameters in this model are β known as the path loss exponent and σ_{dB} known as the variation of received power at a certain distance (see [19] for more information). In our results, we have set the path loss and standard variation parameters equal to $\beta = 2.7$ and $\sigma_{dB} = 6$. As the threshold for the probability to accept a link as an existing link between two nodes, we have used $min.dp = 0.4$. This means that if the link probability between two nodes is greater than 0.4, we consider the link to be an existing link in the network. For the other parameters of the model, we have used the default parameters in NS-2 as shown in Table 1. Note that P_t is the transmitted power, and G_t and G_r are the transmission and reception antenna gains respectively. The parameter L is a system loss, λ is the signal wavelength (c/f, with $c = 3 \times 10^8$ m/s).

TABLE 1
Default parameter values for the shadowing propagation model.

Parameter	Value
P_t	0.28183815 Watt
RXThresh	3.652×10^{-10} Watt
G_t, G_r, L	1
f	914 MHz

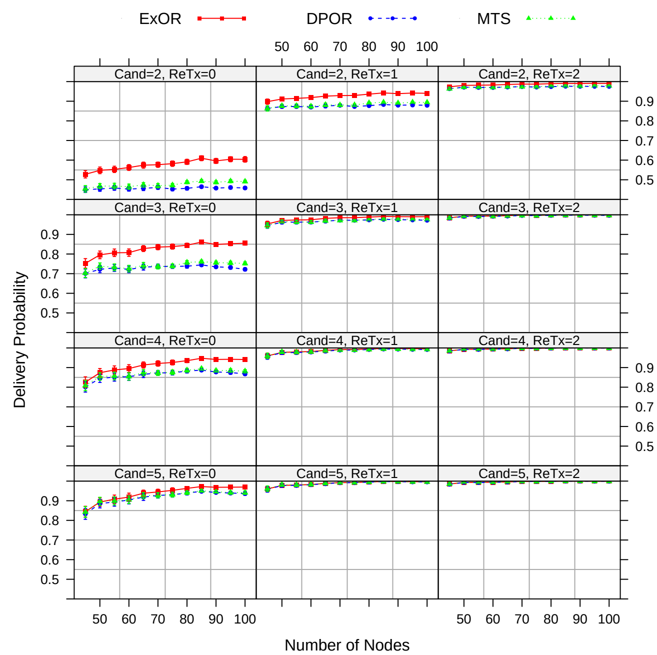

Fig. 4. Delivery Probability varying the number of nodes for different $ncand$ and $re - tx$

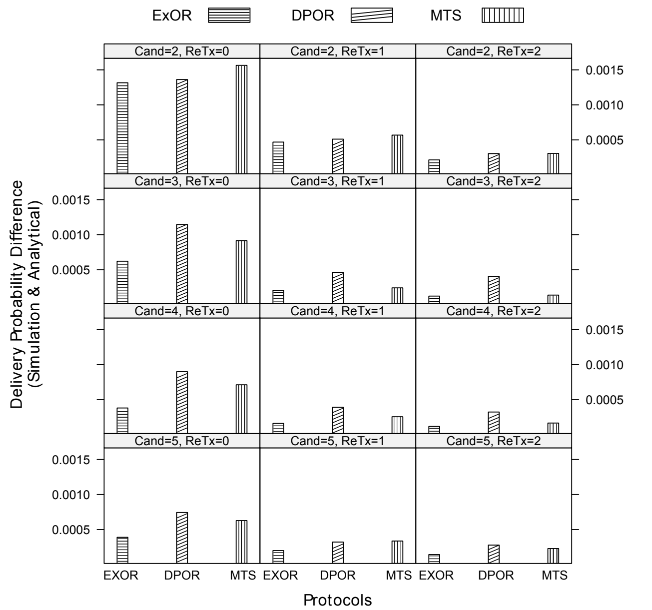

Fig. 5. Delivery Probability differences between simulation and analytical results for different $ncand$ and $re - tx$ (*Perfect* coordination)

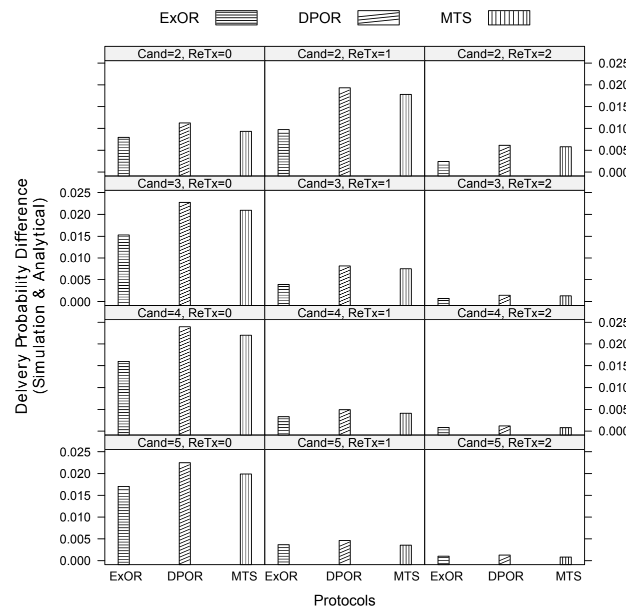

Fig. 6. Delivery Probability differences between simulation and analytical results for different $ncand$ and $re - tx$ (*Timer-based* coordination)

5.3 Metrics under study

To evaluate the performance of the different protocols under study using both the Markov model and the simulation, we have used the different metrics: Probability of successful delivery, Expected Number of Transmissions (ExNT), Probability of the number of transmissions, and Hop-count.

The probability of successful delivery was the probability that a packet is delivered to the destination using OR. For the analytical results, this probability can be calculated using the equations provided in Section 3.3.1. This probability can be calculated by dividing the total number of received data packets at the destination with the total number of sent data packets from the source node. Note that in our simulation results, we have not considered the packets for error control, and the delivery probability is calculated using the number of data packets.

The Expected Number of Transmissions (ExNT) is the most important metric in OR; it captures the expected number of transmissions needed to deliver a packet from a source to a given destination using OR. Using Equation 9, the ExNT can be calculated for the analytical results. To obtain this metric through the simulation, we need to obtain the ratio calculated by dividing the number of transmissions for the packet received at the destination with the number of delivered packets.

The probability for the number of transmissions in the case of delivered packets can be easily obtained, as explained in Section 3.3.3. To obtain this metric through the experimental results, we divided the number of received packets with h transmissions by the total number of packets received at the destination.

Finally, the average number of hop-counts is another metric which can be derived from the Markov model by applying the equations provided in Section 3.3.4. Through the simulation, the average number of hop-counts for delivered packets to the destination is calculated in order to compare the analytical results.

6 Experimental analysis and validation

In this section, we show our analytical and simulation results in terms of the different metrics explained in the section above.

6.1 Delivery Probability

As we have mentioned in Section 5, we implemented the candidate coordination of OR protocols using NS-2 through two different approaches: perfect coordination and Timer-based. In the following text, we show the results in the case of perfect coordination. In our first experiment shown in Figure 4, we varied the number of nodes from $N = 45$ to 100; we also showed the Delivery Probability for each OR protocol under study, varying the number of candidates from $ncand = 2$ to 5 with a different number of re-transmissions (re-tx= $0, 1, 2$). Note that the results presented in Figure 4 were obtained using the proposed Markov model.

As a first observation, we can see that growing the number of nodes in the network increases the Delivery Probability for all OR protocols. This is because a greater number of nodes in the network provides better candidates, which can be chosen by different OR candidate selection algorithms. Furthermore, increasing the number of candidates ($ncand$) with any number of re-transmissions (re-tx) causes a higher Delivery Probability in all protocols. When there are more candidates, there is a greater chance for the packet to progress towards the destination. Obviously, increasing the number of re-transmissions results in having a higher Delivery Probability, since the packet is transmitted more times; it also shows a greater chance of reaching to the next candidate and the destination.

Considering Figure 4, the Delivery Probability gets close to 1 with 2 re-transmissions (re-tx=2) with any number of candidates (see the last column of Figure 4). To sum up this figure, with only a small number of candidates, e.g, ncand=3 and with 2 re-transmissions (re-tx=2), all protocols provide

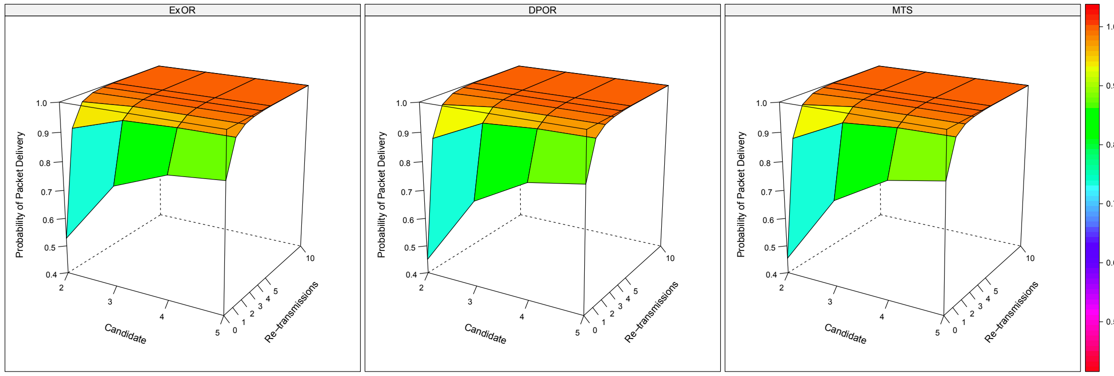

Fig. 7. Delivery Probability varying $ncand$ and $re - tx$ for $N = 45$ nodes

a high packet Delivery Probability. Note that we did not show the results in Figure 4 for a greater number of re-transmissions (re-tx$>$ 2); this is because with re-tx$>$ 2, the Delivery Probability of all protocols under study is equal to 1. In other words, when re-tx$>$ 2 for any number of candidates, the probability of ending at *Dest*, the absorbing state, is equal to 1. As we can see in all scenarios, the Delivery Probability of ExOR is higher than the other two protocols. However, in Section 6.2, we will see that there is a cost to having a higher number of transmissions in the network.

Figure 5 depicts the difference between the analytical results corresponding to Figure 4 and the simulation results obtained using NS-2 in terms of the Delivery Probability. Note that the simulation results were obtained in the case of perfect coordination between candidates. The difference between the analytical and simulation results is so small that is almost negligible. For instance, the minimum difference between the analytical and simulation results is about 1×10^{-4}, while the maximum difference is about 15×10^{-4}. The small shown in Figure 5 is due to the fact that in the simulation, there is a chance of packet collision between transmitted packets; in the Markov model, on the other hand, we have assumed that there is no collision between transmitted packets.

Recall that in the proposed Markov model, we assumed that the highest priority candidate to receive the packet will always forward it, and the other lower priority candidates discard it. In the second method of candidate coordination, which is closer to reality, the Timer-based approach was implemented as explained in Section 5. The difference between the experimental and analytical results when using the Timer-based approach for candidate coordination is shown in Figure 6. Note that we used the Markov model for the analytical results, which assumes that there is perfect coordination between candidates. We can see that the difference between the analytical and experimental results is small and negligible. The minimum difference is about 7×10^{-4} while the maximum value in Figure 6 is about 2×10^{-2}. Comparing Figures 5 and 6, there is a slight difference between analytical and simulation results when there is not a perfect coordination between candidates. This occurs because some of the lower-priority candidates in the Timer-based approach may not detect the transmissions of the higher-priority candidates; consequently, they will forward the packet towards the destination. Nevertheless, the difference between the results obtained through the simulation and the Markov model is very small.

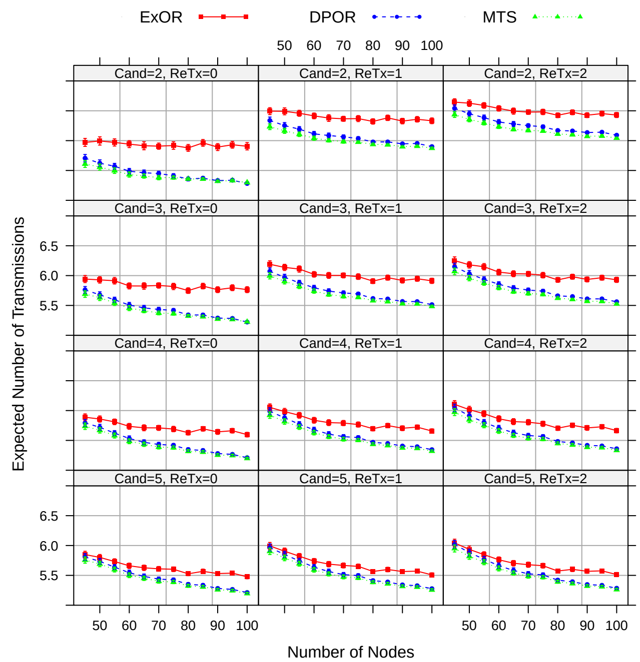

Fig. 8. Expected Number of Transmissions varying the number of nodes for different $ncand$ and re-tx

Figure 7 shows another experiment for the Delivery Probability metric. In this experiment, we fixed the number of nodes to $N = 45$; we also varied the number of candidates and re-transmissions for all OR protocols under study when there is perfect coordination between candidates. Note that we selected $N = 45$ nodes as an example to show the effect of an increase in the number of candidates and re-transmissions. The number of re-transmissions was varied for re-tx$=$ $0, 1, \ldots, 5$ and 10. The behavior of all protocols after 2 or 3 re-transmissions was the same; they also provided the same delivery probabilities. The delivery probabilities of DPOR and MTS in different scenarios are very close to one other; ExOR, as a simple OR protocol, results in a higher Delivery Probability compared to the other protocols.

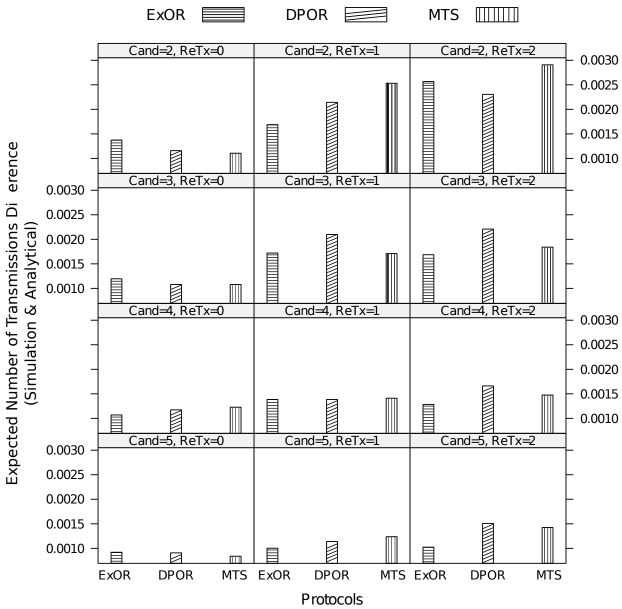

Fig. 9. Expected Number of Transmissions error varying the number of nodes for different $ncand$ and re-tx (Perfect coordination)

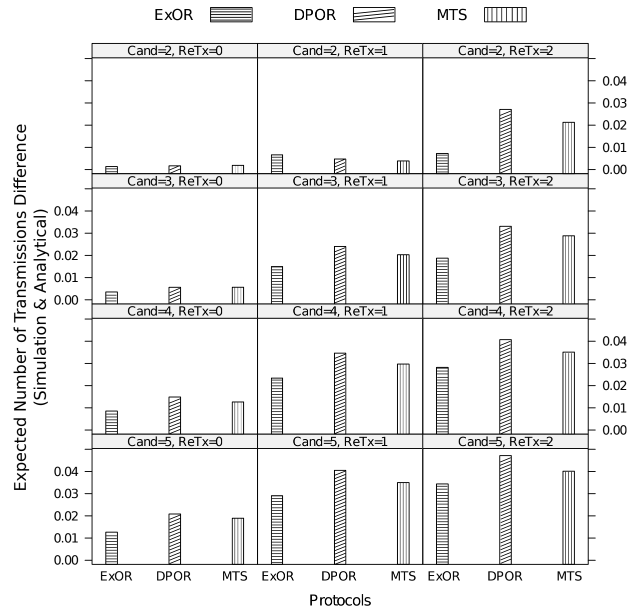

Fig. 10. Expected Number of Transmissions error varying the number of nodes for different $ncand$ and re-tx (Timer-based)

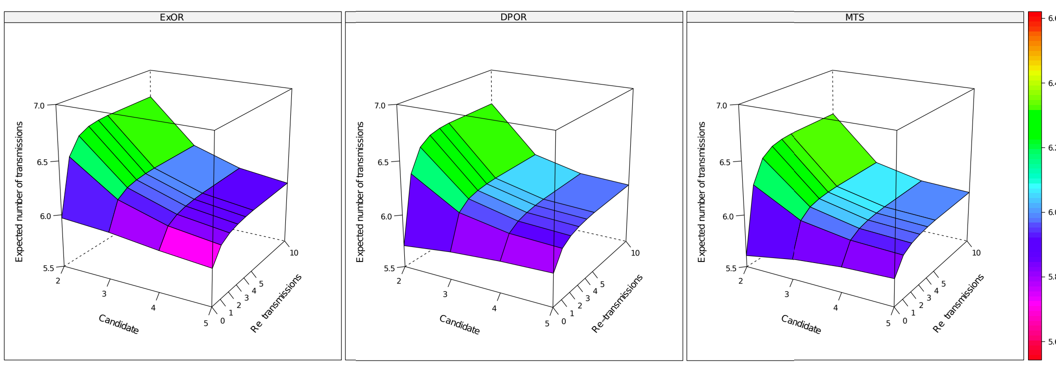

Fig. 11. Expected Number of Transmissions varying $ncand$ and re-tx for $N = 45$ nodes

6.2 Expected number of transmissions

In this section, we show both the analytical and simulation results in the event of perfect and Timer-based coordination for the ExNT metric.

Figure 8 shows the Expected Number of Transmissions (ExNT) from the source to the destination, obtained through the Markov model; the number of nodes for different numbers of candidates ($ncand = 2, 3, 4, 5$) and re-transmissions re-tx= $0, 1, 2$ are varied. As a first observation, ExOR presents a higher ExNT than other protocols in all cases, while MTS shows the minimum level. Recall that MTS uses EAX to find the optimum CS, so that the ExNT resulting from those sets is minimized. In addition, increasing the number of candidates causes a decrease in the ExNT. This is due to the fact that the packet can progress farther towards the destination and can reach it with a smaller number of transmissions when there are more candidates. Furthermore, increasing the number of re-transmissions causes a higher ExNT, but this stops when re-tx$>$ 2. This occurs because when the number of re-transmissions is larger than 2 (re-tx$>$ 2), the Delivery Probability is equal to 1. Thus, additional transmissions are not required (see Figure 4).

We have shown the difference between the experimental and analytical results when the candidates achieve perfect coordination in Figure 9. The difference between the simulation and the analytical results is very small and ranges from 10×10^{-4} to 30×10^{-4}; these are negligible values. This small difference results from experimental scenarios in which a packet may collide with another transmission, consequently requiring re-transmission of the packet by the node; this situation cannot, however, occur in the Markov model.

We have drawn the difference between the ExNT of the analytical results and the experimental results when using the Timer-based approach for coordination, as depicted in Figure 10. The figure shows that with the Timer-based coordination, the experimental results are closer to the equivalent analytical values; furthermore, the differences obtained range from 0.001 to 0.04, which can be considered a negligible value in terms of the ExNT.

Furthermore, Figure 11 shows the Expected Number of Transmissions (ExNT), varying the number of candidates and re-transmissions for different OR protocols while the number of nodes is set to $N = 45$. Both DPOR and MTS, in all cases, outperform the well-known ExOR in terms of ExNT. Increasing the number of re-transmissions in all protocols results in decreasing the ExNT. Considering re-tx= 0 in ExOR, we can see that by increasing the number of candidates from 2 to 5, the ExNT of ExOR will decrease from 5.97 to 5.84, and the ExNT for the other two protocols (DPOR and MTS) will increase slightly from 5.60 to 5.75. We obtained the same results through the simulation experiments, with some small differences as shown in Figure 9.

6.3 Probability Distribution of the number of transmissions

The other metric that can be derived from the proposed Markov model is the probability distribution of the number of transmissions for packets delivered to the destination. Figure 12 depicts this metric for a different number of candidates ($ncand = 2, 3, 4, 5$) and re-transmissions (re-tx= $0, 10$) for $N = 45$ and 100 nodes; here we refer to these quantities of nodes as *low* and *high* density networks respectively. Note that this metric can be obtained with any number of re-transmissions; we have selected re-tx= 0 and 10 as two examples.

As a first observation, we can see that MTS outperforms other protocols under study by delivering a higher number of packets with a smaller number of transmissions sent to the destination. Furthermore, increasing the number of candidates or re-transmissions in all cases ($N = 45, 100$ and re-tx= $0, 10$) results in increasing the probability of delivering packets to the destination with a smaller number of transmissions. For instance, consider the MTS protocol in the low density network ($N = 45$) in the case where re-tx= 10. When the number of candidates is equal to 2 (ncand= 2), about 30% of the packets received at the destination are delivered with only 5 transmissions. On the other hand, 40% of the packets received at the destination are delivered by only 5 transmissions in the same scenario with 5 candidates (see row 3 of Figure 12).

6.4 Average hop-count

Figure 13 shows the average hop-count for the packet received at the destination, varying the number of nodes for different numbers of candidates ($ncand = 2, 3, 4, 5$) and re-transmissions (re-tx= $0, 1, 2$). In all cases, the curves depict a reduction in the number of hop-counts required to reach the destination when the number of candidates is increased. This occurs because a large number of candidates allows the packets to progress towards the destination, and to approach it with fewer transmissions; therefore, the hop-count number is reduced. Note that when there are no re-transmissions in the network (re-tx= 0), the average hop-count and the ExNT are exactly the same (see the first column in Figure 13 and 8). We can also observe that MTS and DPOR outperform ExOR, as described in Figure 13.

We have also shown the difference between the average hop-count obtained from the model and the experimental results in Figure 14. Like the other metrics explained in Sections 6.1 and 6.2, the difference between the analytical and simulation results is very small; it ranges from 6×10^{-4} to 14×10^{-4}. In addition to the results demonstrating perfect coordination between candidates, Figure 15 shows the same results in the case of the Timer-based coordination between candidates. When the Timer-based coordination was used, the minimum and maximum difference between the analytical and experimental results in terms of hop-count is about 1×10^{-3} and 7×10^{-2}; this is small and negligible in terms of average hop-count.

7 Conclusion

Opportunistic Routing (OR) is a routing mechanism that increases reliability in wireless networks. However, selection of candidates has a great impact on network performance. Most of the existing research work focuses on this aspect from a simulation-based approach.

In this paper, we have presented a Markov Chain model that enables the performance evaluation of OR-based protocols for wireless mesh networks in a very simple but effective way. We show how the proposed Markov model is valid for any type of network topology and for any candidate selection algorithm, considering the number of re-transmissions in each node when candidates have not received the packet. The proposed model takes into account the number of re-transmissions and is valid for any number of candidates; thus, both parameters can be easily evaluated when designing a new OR protocol. Hence, our model can provide insights to OR developers, offering guidelines that can be used towards the design of future generation of OR protocols for more complex networks.

As some potential future work, the current Markov model can be extended towards mobile networks such as mobile ad hoc network and vehicular networks, where the network topology changes frequently. Further studies may investigate such networks with a dynamic environment.

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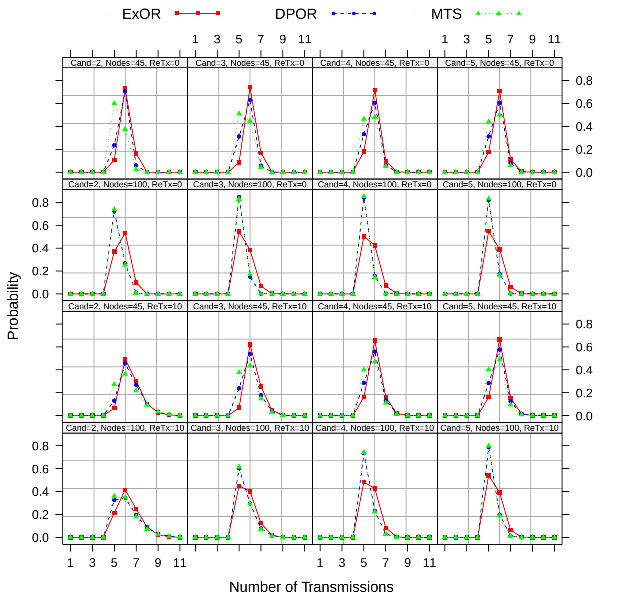

Fig. 12. Probability of number of transmissions varying $ncand$, re-tx= 0,10 and $N = 45$ and 100 nodes

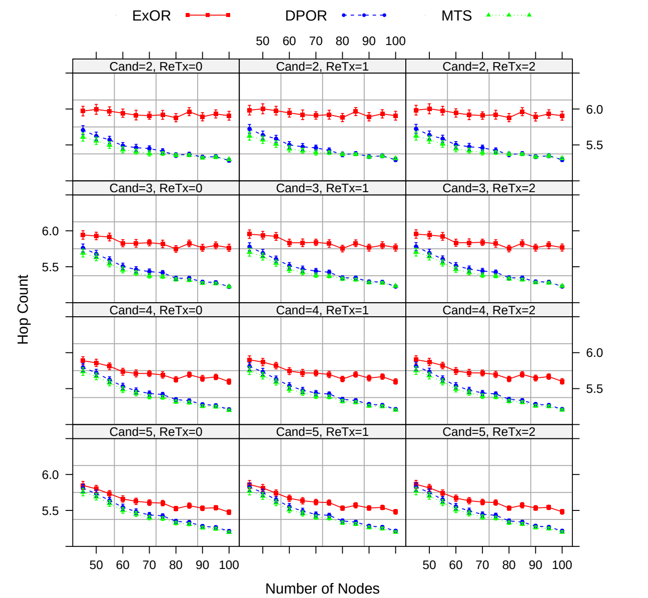

Fig. 13. Hop-count varying the number of nodes for different $ncand$ and re-tx

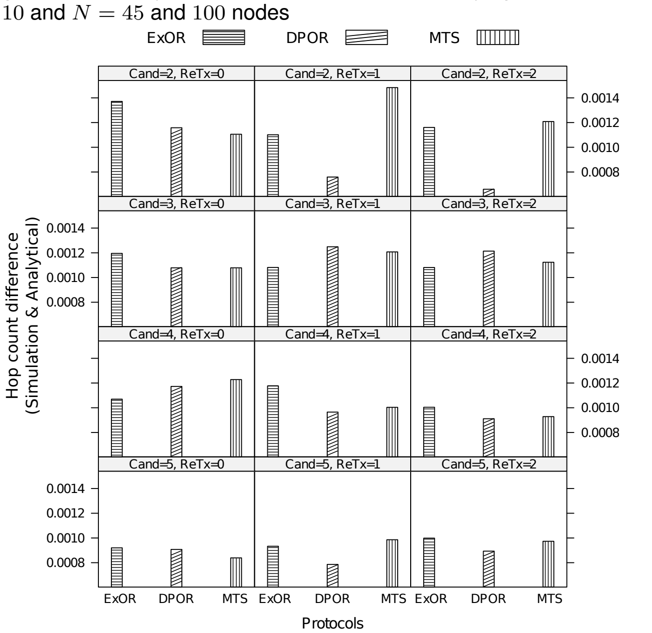

Fig. 14. Hop-count error when varying the number of nodes for different $ncand$ and re-tx

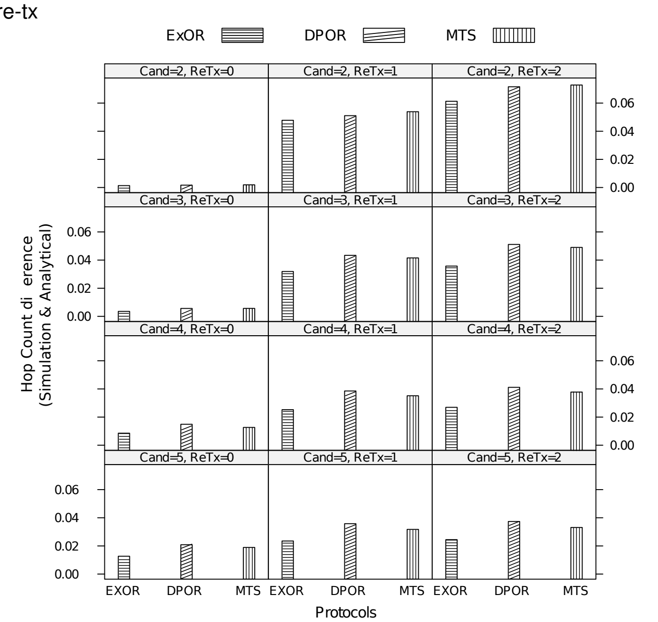

Fig. 15. Hop-count error varying the number of nodes for different $ncand$ and re-tx (Timer-based approach)

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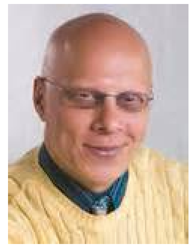

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